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THE SCALE SIZE OF SCINTILLATION-PRODUCING IRREGULARITIES IN THE AURORAL IONOSPHERE

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ABSTRACT

Measurements of the transverse scale of F-layer irregularities, based on radio-star observations from College, Alaska, at frequencies of 68 and 223 MHz, are reported. Analysis by the two-frequency scintillation-ratio technique yields typical scales of 600 to 700 meters for mid-auroral latitudes. Typical scales of one kilometer are found for higher-latitude irregularities. The latter show increasing scale with increasing magnetic index. Analysis by the two-frequency correlation technique produces erroneously small scales due to refraction effects.

ACKNOWLEDGMENTS

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INTRODUCTION

Several techniques have been developed for measuring the scale size of ionospheric irregularities which produce radio-star scintillations. The most commonly employed is the familiar spaced-receiver method, described for instance by Ratcliffe (1956, section 11.3). At least two other techniques also have been employed. First, Aarons and Guidice (1966) have estimated irregularity size by observing the decrease in scintillation displayed by sources with increasing angular dimensions. Second, Fremouw (1966) has obtained scale sizes from observations of visibility fades.

Briggs and Parkin (1963) have suggested another technique, heretofore untried, which does not require spaced receivers, multi-source observations, or the severe scatter conditions of a visibility fade. Based on simultaneous observations at two frequencies, the technique's theoretical foundation was refined by Budden (1965) to account for anisotropic irregularities in a region of arbitrary thickness. In the present work we have applied Budden's refinement to observations in the northern auroral zone.

In the technique which we have used, the observable quantity is the ratio of amplitude fluctuation at two frequencies. Budden also analytically described the correlation between amplitude fluctuations at two frequencies. We have performed the correlation analysis for some of our data, and we shall discuss those results briefly at the end of the paper.

Several ionospheric parameters other than scale size affect both the two-frequency scintillation ratio and the two-frequency correlation. They include the center height and thickness of the diffracting region and the axial ratio of the ion-density irregularities involved.

Budden (1965, section 6) pointed out that the effect of region thickness on two-frequency correlation is negligible so long as it is large compared with the scale of irregularities. We have found this to be true also for the two-frequency scintillation ratio. The effect of field alignment precludes predicting general results for all observing stations and all sources. Therefore the location of the observatory and the angular position of the source relative to the geomagnetic field must be taken into account.

In the present work we have used a result of Budden's to calculate the combined center height and scale size dependence of the two-frequency scintillation ratio given a thick region (100 km), a range of axial ratio, and the circumstances of our experiment. Our observing frequencies were 68 and 223 MHz and the receiver site was located near College, Alaska (64.9°N, 147.8°W, gg; 64.6°N, 256.6°E, gm). A single circumpolar source, Cassiopeia A, was tracked with simply (i.e., noncoherently) detecting phase-sweep interferometers having east-west baselines of about 220 meters.

In the next section, using Budden's theory, we shall discuss the behavior of the two-frequency scintillation ratio under our experimental conditions. Thereafter we shall present experimental data followed by results for the scale size of auroral-zone irregularities based on the model calculations. Finally we shall briefly discuss the observed correlation between amplitude scintillations at the two frequencies.

MODEL CALCULATIONS

We measured the ratio, S_{68}/S_{223}, of scintillation index at 68 MHz to that at 223 MHz, with the index S_i defined as the mean fractional fluctuation in received intensity, $\overline{|P_i - \overline{P}_i|}/\overline{P_i}$. Briggs and Parkin (1963, section 8) have discussed the equivalence of S_i as defined above to other measures of amplitude or intensity scintillation. Since Budden's equation (49) is proportional to S_i^2, it is a simple matter to adapt it to relate two-frequency scintillation ratio to ionospheric parameters.

We have accounted for geometric factors on the basis of an earth-centered but axially tipped magnetic dipole field. These factors include the azimuth of the source relative to the horizontal component of the magnetic field, the incidence angle of the radio wave on the ionosphere, and the magnetic dip angle beneath the point of ionospheric penetration. In the calculations the long dimension of the irregularities was assumed to be parallel to the magnetic field.

Fig. 1 shows the dependence of S_{68}/S_{223} on transverse irregularity scale size for three assumed diffraction-region center heights and a range of axial ratio from 5 through 20. As a definition of scale we are using the distance over which the ionospheric autocorrelation function drops to 1/e. Axial ratio is defined here as the ratio of scale along the field to that transverse to the field. The figure pertains to upper transit of Cas A at College, corresponding to a zenith angle of about 6 degrees (south).

At the top and bottom of Fig. 1 the curves merge to limiting values of scintillation ratio. These limits correspond to the near and far zones where $S_{68}/S_{223} = (\lambda_{68}/\lambda_{223})^2$ and $S_{68}/S_{223} = \lambda_{68}/\lambda_{223}$, respectively, as discussed by Briggs and Parkin (1963, section 5.3).

In the near and far zones one may hope to set respectively lower and upper limits on irregularity scale size. The transition zone between the limits represents a range in which one may hope to obtain explicit measurements of scale if values of height and axial ratio can be established or reasonably assumed.

A set of curves similar to those in Fig. 1 can be computed for each angular position of the source. Alternatively the position dependence of scintillation ratio for a given set of ionospheric parameters can be presented as in Fig. 2. The smooth curves show zenith-angle dependence given a single axial ratio and two values each of height and scale.

It is important to note that an irregularity region of geographically uniform parameters results in a predicted minimum in scintillation ratio near lower transit. Also the curves are not quite symmetrical about upper or lower transit for field-aligned irregularities. For an axial ratio of five, which was used for Fig. 2, the asymmetry is

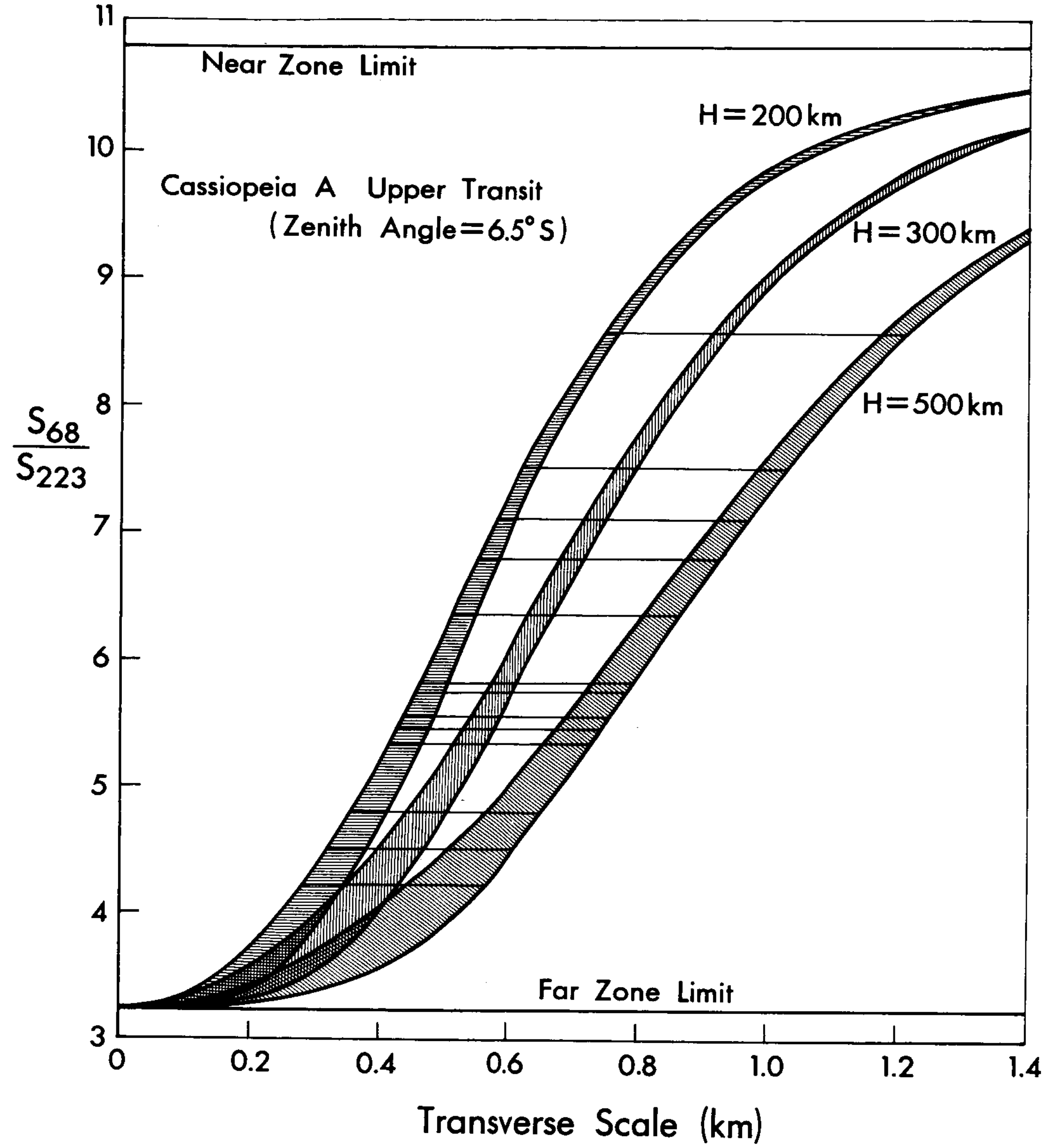

Fig. 1. Scintillation ratio versus transverse scale for one source position and three values of diffraction-region center height, H. The top and bottom of each shaded region correspond to an axial ratio of 20 and 5, respectively. The horizontal bars represent observed values of ratio.

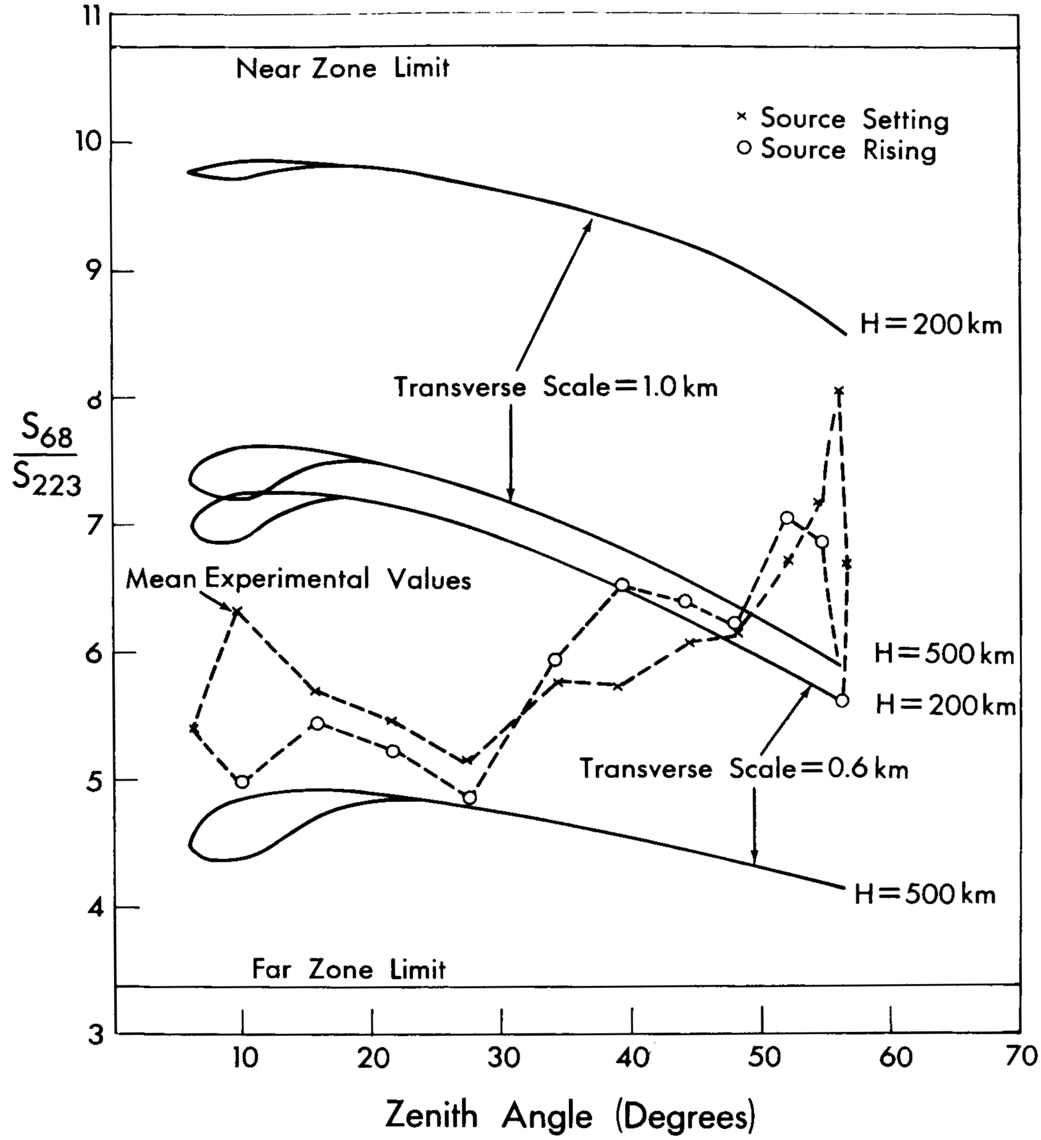

Fig. 2. Scintillation ratio versus Cassiopeia A zenith angle for an axial ratio of 5 and two values each of height and transverse scale (smooth curves). The broken curve represents mean observed values of ratio.

noticeable only near upper transit. The decrease in scintillation ratio just past upper transit results from the irregularities being observed nearly end on.

OBSERVED SCINTILLATION RATIOS

We obtained digital recordings of Cas A amplitude fluctuation simultaneously on 68 and 223 MHz for three consecutive months starting in October of 1965. The sample rate varied between 15 and 120 per minute. Hourly averages of scintillation ratio were computed when S_{223} exceeded 0.04.

Fig. 3 shows 244 values of scintillation ratio as a function of zenith angle. Nearly all the data points fall within the intermediate zone, allowing explicit measurement of scale if other parameters are known. Average values of the observed ratios are shown in the broken curve of Fig. 2. Comparison with the theoretical curves shows a marked discrepancy for the greater zenith angles. The experimental data follow a trend upward toward the near-zone limit, while the theoretical curves predict an opposite trend.

Orhaug (1965, section C5) has reported a similar discrepancy between single-frequency (150 MHz) observations and simple theory at geographic and geomagnetic latitudes comparable to our own. He listed four possible explanations as follows:

"1. The layer height is gradually decreasing with increasing latitude.

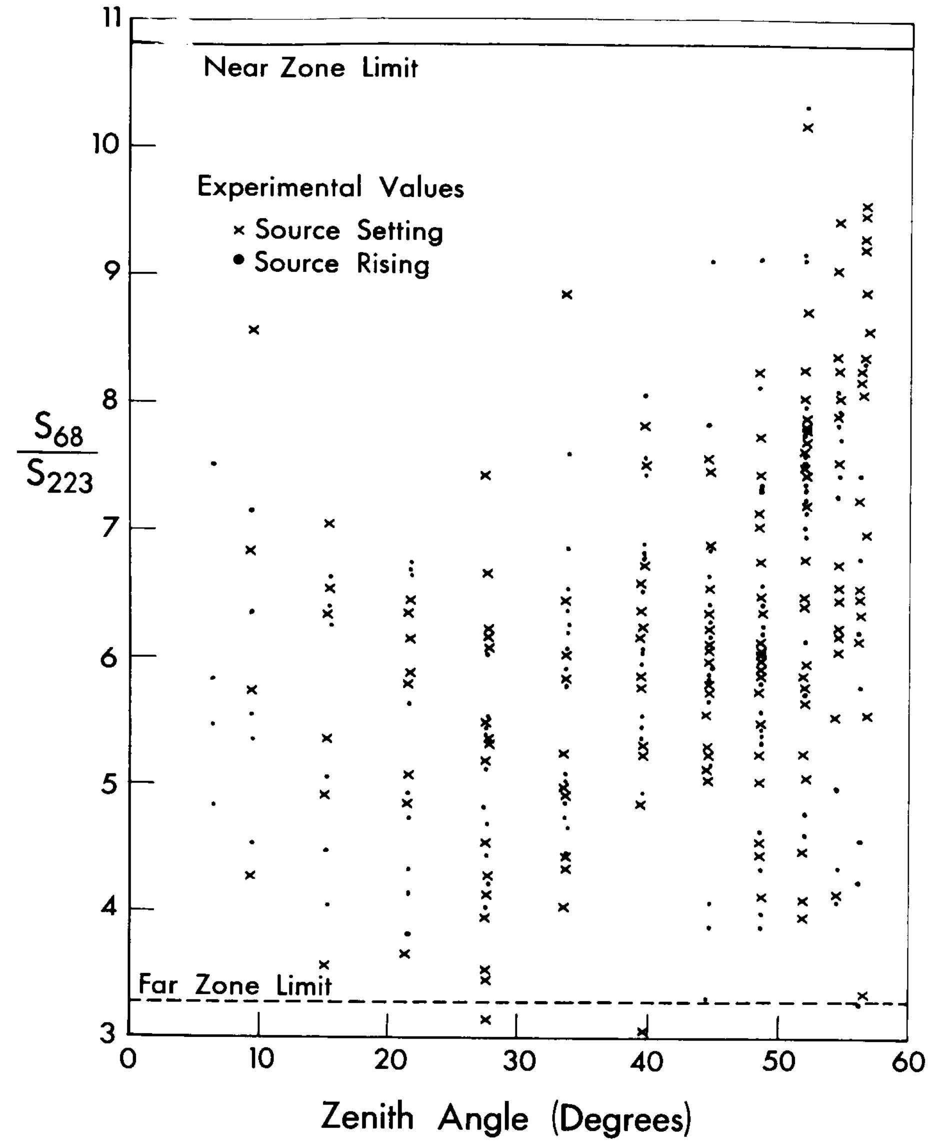

Fig. 3. Observed values of scintillation ratio versus zenith angle.

2. The average dimension of the irregularities is gradually increasing with increasing latitude.

3. The spatial irregularities are anisotropic.

4. The intensity of the fluctuations of refractive index is gradually increasing with latitude."

Orhaug commented further, "Of these assumptions, the last two are considered to be the most probable."

On the basis of observations then available, we would have agreed with Orhaug's concluding remark. However, our two-frequency observations point instead to his first two alternatives. Budden's theory, which we have used in computing the smooth curves of Fig. 2, accounts for anisotropy. While the curves shown are for an axial ratio of 5, we have computed similar ones for axial ratios up to and including 20, and they all display minima at lower transit.

We would not dispute the possibility of an increase in intensity of irregularities with increasing latitude. However, as discussed by Briggs and Parkin (1963, section 5.3), such an effect would not be reflected in our two-frequency observations.

Thus we conclude that ionospheric irregularities north of College, Alaska, display either a decrease in height, an increase in scale, or both, with increasing latitude. (That the observed variation is more likely latitudinal than diurnal will be discussed later.)

ASSUMPTIONS AND ANALYSIS

The theory of Budden (1965), which we have used, is based on assumption of an optically thin scattering region. A study of radio-star visibility during our observing period (Fremouw, 1966) has indicated that this condition prevailed at our frequencies. Furthermore, temporal autocorrelation functions computed from our data usually were nearly identical at the two frequencies indicating that the same scale predominated in the ground shadow patterns at each frequency. This is inconsistent with an optically thick scattering region.

For an optically thin region there are two sources of error in determination of scintillation index which may be ignored in our analysis because they cancel when the scintillation ratio is computed. The first is that which occurs when the wavefront arriving at the ground contains structure of a scale comparable to the antenna separation employed. Such loss of correlation produces an erroneous decrease in the measured value of S_i, as has been discussed quantitatively by Fremouw and Lansinger (1966). For an optically thin region the scale of the ground shadow pattern is essentially independent of frequency. Given this condition, the two-frequency scintillation ratio is not modified by such a reduction in correlation when equal baselines are used.

The second potential problem is the decrease in S_i associated with finite source size, as discussed by Briggs (1961). The error arises when the displacement between the ground shadow patterns from opposite sides of the source becomes an appreciable fraction of the pattern scale. Again for an optically thin region the effect is independent of frequency. Accordingly the two-frequency scintillation ratio is unaffected by finite source size.

A considerable range in height has been measured for auroral-zone irregularities. However, the most comprehensive set of measurements available (Liszka, 1964) shows a distinct peak in the distribution of scintillation-producing irregularities at about 300 km, with 75 percent of the data points falling between 200 and 500 km. For simplicity in our analysis we have taken all region center heights to be within the latter range. When it has been necessary to assume a specific center height, we have used 300 km.

Compared with height determinations, there are relatively few measurements of axial ratio in the auroral zones. Liszka (1963) has reported six observations at an auroral latitude, the measured ratio ranging from 8 through 21. Observing from Cambridge, Jones (1960) reported a median value of slightly greater than 5 when his line of sight traversed the auroral ionosphere. (Note that the observations by Flood (1965) of alignment with the long dimension transverse to the geomagnetic field were for the special conditions of visibility fades and may pertain to E-layer irregularities.)

Our calculations of scintillation ratio based on Budden's equation (49) have shown little sensitivity to axial ratio except near the condition of isotropy. For a given center height, curves similar to those in Fig. 1 differ most for axial ratios of 1 to 2, less for ratios of 2 to 5, and very little for ratios of 5 to 20. Ratios less than unity were not considered. The greatest effect of varying axial ratio between 5 and 20 occurs near upper transit, the case shown in Fig. 1. For most source positions the two sets of curves are essentially identical.

Thus over the range of available auroral-zone axial-ratio measurements (excluding visibility fades), our results may be expected to be essentially independent of axial ratio. For purposes of analysis we have assumed the value 5.

The method of analysis employed is illustrated in Fig. 1. The horizontal bars indicate experimental values of scintillation ratio. The limits of the bars are set by the assumed range of height (200-500 km) and the assumed range of axial ratio (5-20). The projection on the abscissa of a particular measurement bar yields the range of scale size consistent with the assumed height and axial ratio limits. Graphs similar to Fig. 1 were constructed for all zenith angles observed, with each graph used to cover a ten-degree range. Where necessary, separate graphs were used for source-rising and source-setting observations in the same zenith-angle range.

Combining results obtained in the above manner for different portions of the sky results in a histogram which gives the occurrence distribution of transverse scale size. It is to be noted that the results are based on assumption of a uniform distribution between 200 and 500 km for region center heights. This assumption generally tends to broaden resulting histograms compared with results based on the peaked height distribution observed by Liszka (1964), although it reduces the histogram's base width.

Each measurement of scintillation ratio was determined from one hour's data containing about 900 digitized samples at each of the two observing frequencies. The basic measurement uncertainty and that arising from one-hour averaging are negligible compared with that produced by the uncertainty in height. Therefore the former two sources of error were ignored in the analysis.

RESULTS FOR IRREGULARITY SCALE

When all data were analyzed it was found that five observations corresponded to far-zone conditions. The remaining 239 observations produced measurements of scale size. The result, given by the solid histogram in Fig. 4, shows a considerable preference for transverse scales on the order of 0.6 to 0.8 km. This is in close agreement with five of the six transverse-scale measurements reported by Liszka (1963, section 3C).

If the data are split between the seven most northerly hour angles and the remainder, two quite different occurrence distributions of scale size result. This is shown in the broken histograms of Fig. 4. It is seen that the peak in the overall distribution results mainly from the lower-latitude irregularities, whose scales peak at 0.6 to 0.7 km. The higher-latitude distribution peaks near 1.0 km and is relatively broader.

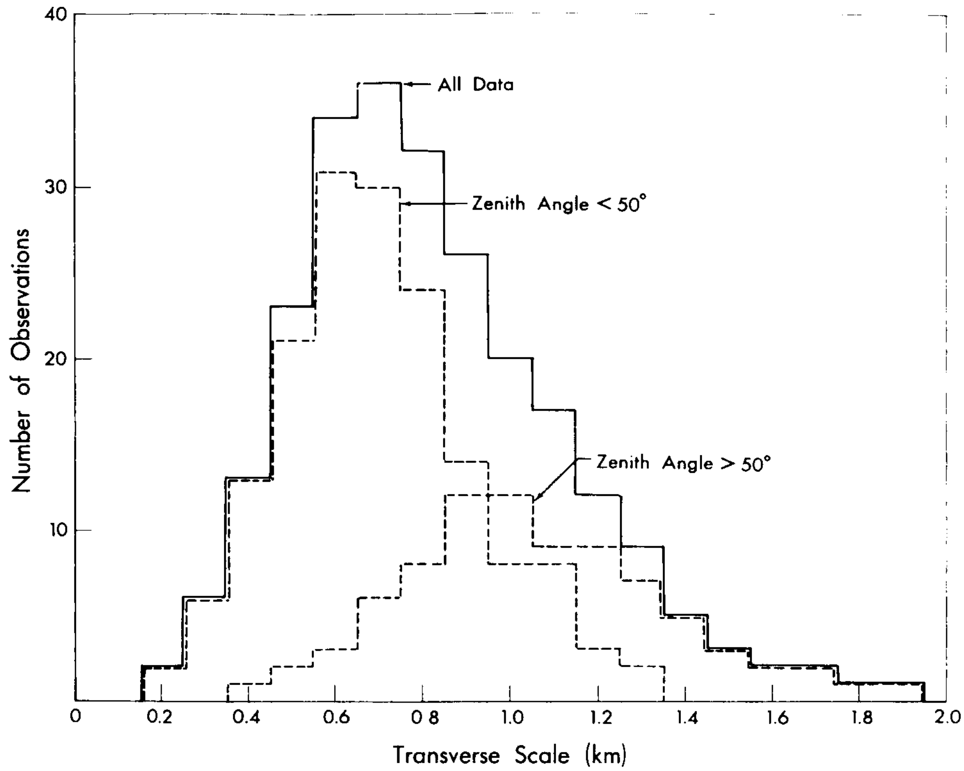

Fig. 4. Observed distribution of transverse scale size for all data and for two ranges of zenith angle. Analysis based on assumption of uniform distribution between 200 and 500 km for diffraction-region center heights.

Earlier in this paper we concluded that our observations imply either a decrease in height or an increase in scale with increasing latitude. Several workers have measured irregularity heights in the auroral zone (Basler and Dewitt, 1962; Hook and Owren, 1962; Beynon and Jones, 1964; Liszka, 1964; Frihagen and Tröim, 1961). Yet, to our knowledge, there has been no report of an observed decrease in height with increasing latitude.

Therefore we have analyzed our data on the assumption that there is no systematic dependence of height on latitude. The result for an assumed height of 300 km is the scatter plot of transverse scale versus Cas A hour angle which is shown in Fig. 5a. A distinct increase in scale for the more northerly hour angles is evident.

It might be argued that the variation in scale displayed in Fig. 5a represents a diurnal dependence rather than a latitudinal one since our observations were taken over only part of a year. Therefore we have plotted transverse scale versus 150-degree-west-meridian time in Fig. 5b. It will be noted that the general scatter of the points in Fig. 5b is greater and the systematic trend less distinct than in Fig. 5a. This implies that the observed trend is a stronger function of sidereal time (and therefore of latitude) than of solar time. We cannot state conclusively, however, that there is no diurnal dependence. This possibility should be checked either by a full year's observations with a radio star or by some other means.

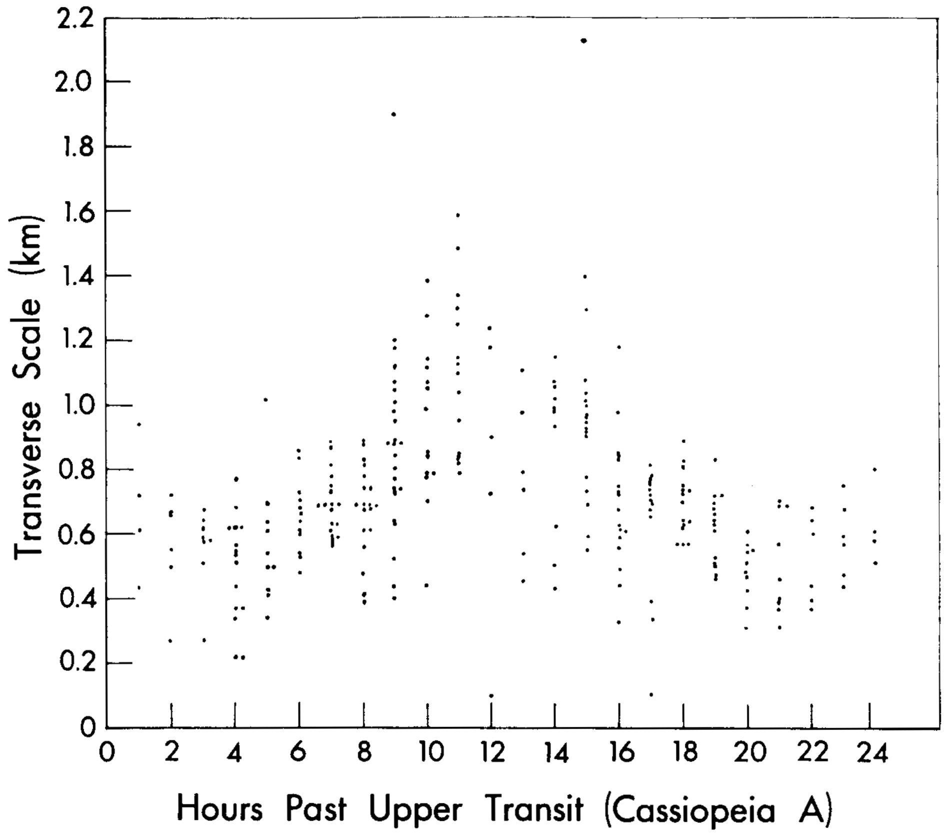

Fig. 5a. Observed values of transverse scale versus Cassiopeia A hour angle for an assumed height of 300 km (3 months' data).

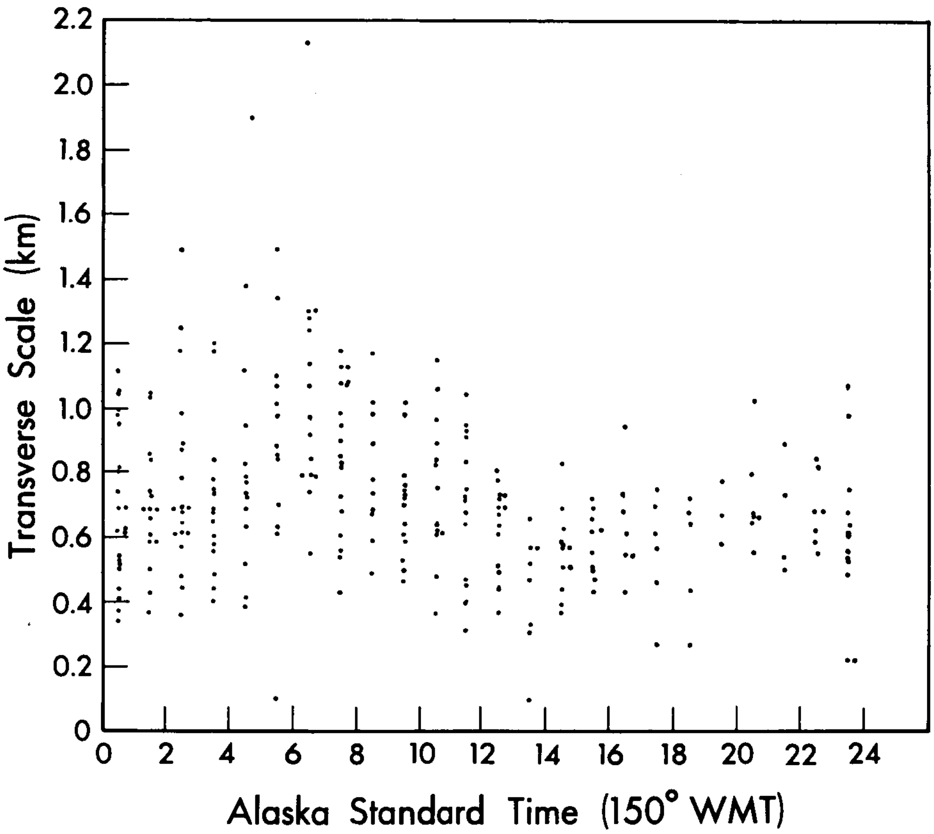

Fig. 5b. Observed values of transverse scale versus Alaska Standard Time for an assumed height of 300 km (3 months' data).

Another distinct difference between the more northerly group of data and the remainder lies in their respective dependence on magnetic activity. A scatter plot of all measured scales versus College K index shows no statistically significant trend. However, when only the measurements obtained at the seven most northerly hour angles are used, there is a clear and somewhat surprising increase in scale with increasing magnetic activity, as shown in Fig. 6. All the points in Fig. 6 are from the northern group of measurements. The circled points are from the three most northerly hour angles. The latter show the same trend as the larger group of data and somewhat less scatter.

There is again the possibility that the magnetic dependence of our data results from decreased height during increased magnetic activity rather than from increased scale. However, Liszka (1964) has analyzed his height observations in terms of K index. He found no significant difference in the height distribution of irregularities for local K indices of 0 through 6.

It could be that such an effect was masked in Liszka's results by the strong latitudinal control which we have observed. Again, this possibility ought to be checked. On the basis of currently available information, however, we suggest that a dependence of scale on magnetic activity, such as that shown in Fig. 6, exists for scintillation-producing irregularities above about 67° latitude (geographic or geomagnetic).[1]

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[1]Geographic and geomagnetic latitude are nearly equal in the region of interest.

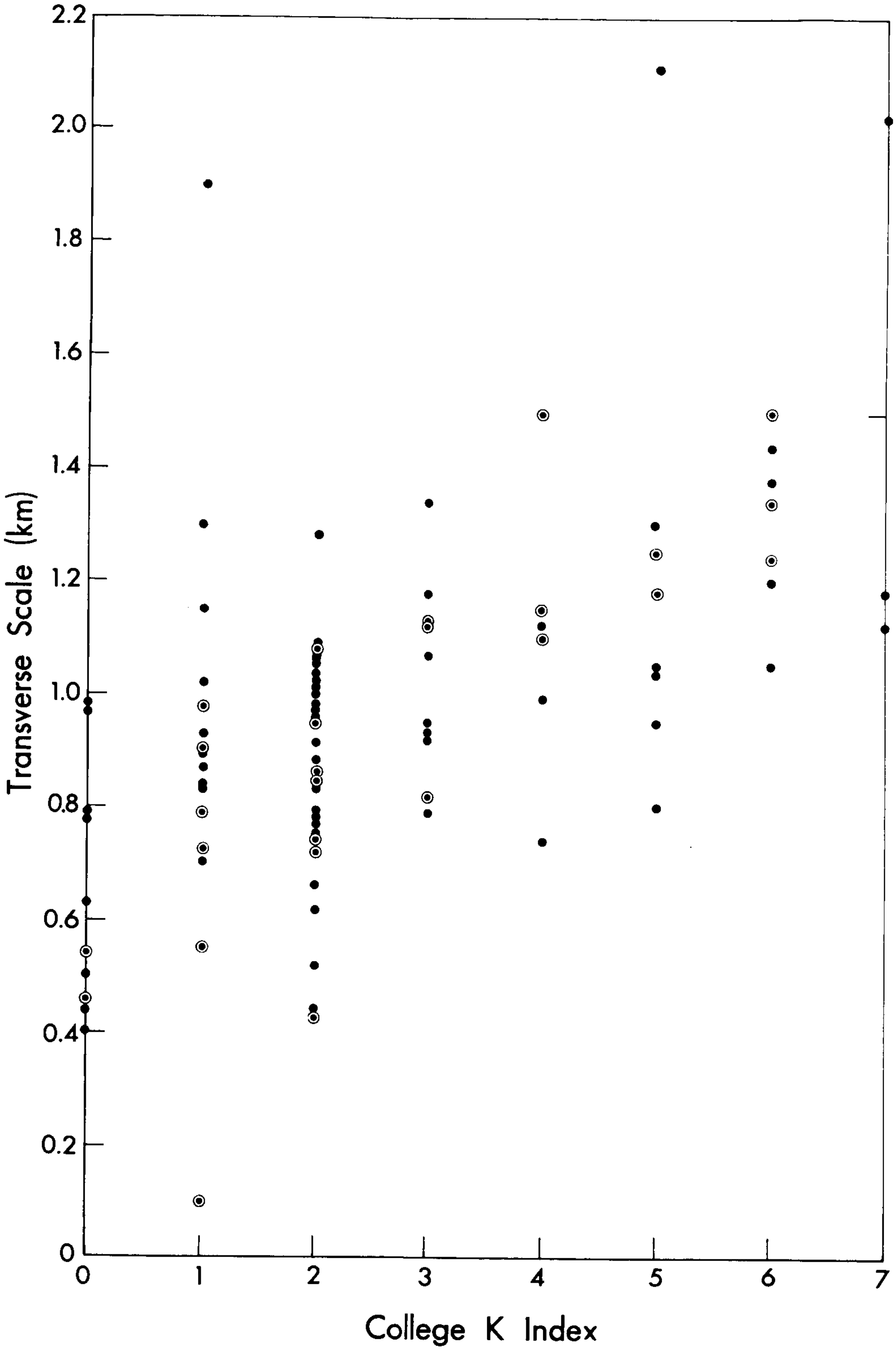

Fig. 6. Observed values of transverse scale versus College K index for an assumed height of 300 km. All data from seven most northerly hour angles; circled points from three most northerly hour angles.

CORRELATION BETWEEN AMPLITUDE SCINTILLATIONS AT TWO FREQUENCIES

From 91.5 hours of data we made 50 calculations of observed correlation for periods on the order of an hour each during which the records appeared to exhibit reasonable statistical stationarity. The observed correlation coefficients are presented in Fig. 7 as a function of zenith angle. The representative error flags in the vertical direction indicate the 95-percent confidence limits in determination of the correlation coefficient. The limits in the horizontal direction indicate the typical variation in zenith angle of the source over the period of a data run.

The results were analyzed for transverse scale size in a manner similar to that described above for scintillation ratio. In all instances corresponding results were available from the scintillation-ratio analysis, although the two sets of results seldom represented strictly simultaneous observations.

In general the agreement between the two sets of results was not close. The scales obtained from the correlation analysis on the average (and rather consistently) were smaller than those obtained from the scintillation-ratio analysis. This corresponds to observed values of correlation which are too small to be compatible with the observed values of scintillation ratio.

On the average the discrepancy between the two sets of results was greater for the larger zenith angles. This suggests that refraction is responsible. The residual discrepancy at small zenith angles can be

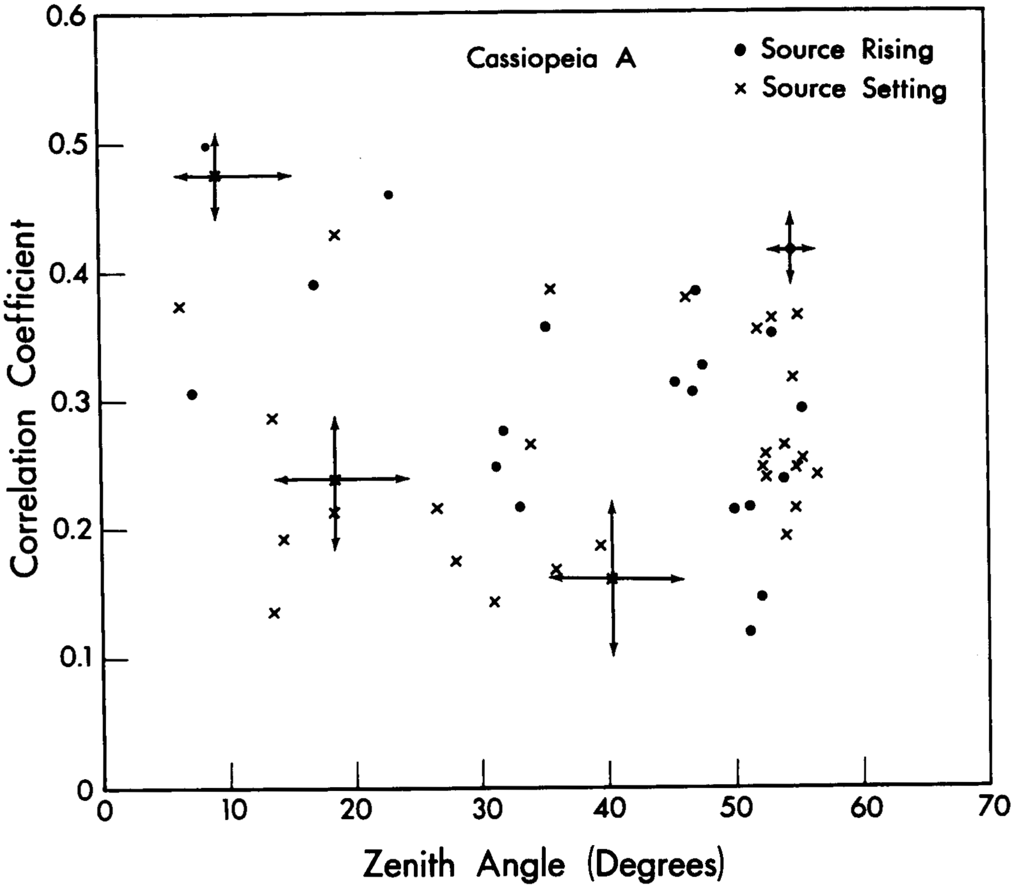

Fig. 7. Observed values of correlation between amplitude variations at 68 MHz and 223 MHz versus zenith angle.

explained on the basis of refraction in large-scale ion-density gradients below the scintillation-producing region.

A differential refraction angle at the two wavelengths will result in a separation of the ground diffraction patterns. An angle as small as 3 minutes of arc will result in a separation which can be an appreciable fraction of an irregularity width. This would occur for a 300-km height with scale sizes of the order obtained from the scintillation-ratio analysis. Muldrew (1965) and Sharp (1966) have reported the existence of high-latitude ionization troughs. It is to be expected that gradients associated with these troughs would produce such refraction.

In contrast to the statistically significant correlation shown in Fig. 7 for observations at 68 and 223 MHz, Chivers (1960) reported insignificant correlation at 26 and 79 MHz. It is to be noted that while a 3:1 frequency ratio was used in both sets of observations, the lower observing frequency in our observations is considerably higher than that of Chivers.

It was pointed out by Budden (1965) that the correlation will be high provided the difference in distance, $\Delta\ell$, traveled to the first Fresnel zone at the two observing frequencies is small compared to the scale size. Given a distance z to the region and denoting the velocity of light as c, this difference is

$$\Delta\ell = \left(\frac{zc}{f_1}\right)^{\frac{1}{2}} \left[1 - \left(\frac{f_1}{f_2}\right)^{\frac{1}{2}}\right], \qquad f_2 > f_1$$

It is clear that either an increase in the ratio f_2/f_1 or a decrease in f_1 will result in an increase in $\Delta\ell$. The Alaska observations yield values of $\Delta\ell$ smaller than those of Chivers by a factor of about 1.6. Thus for the same irregularity sizes and distances to the diffracting region, the Alaska data would be expected to show a higher correlation. Our observations have borne out this expectation, with the magnitude of the observed correlation lower than that anticipated but substantially higher than that reported by Chivers (1960). In the absence of refractive effects the observed correlation would be still higher.

CONCLUSION

From analysis of our two-frequency observations by the scintillation-ratio technique, we have reached the following conclusions:

1. Auroral-zone scintillation-producing irregularities at geographic or geomagnetic latitudes below 67° typically have scales transverse to the geomagnetic field on the order of 600 to 700 meters.
2. Above this latitude typical transverse scales are on the order of 1 kilometer.
3. The more southerly of these irregularities display no general dependence of scale on magnetic K index, while the more northerly ones increase in size with increasing magnetic activity.

The above conclusions are based on assumption of F-layer center heights for the diffracting region and exclude the special aurorally associated conditions of radio-star visibility fades. Fade-producing irregularities are considerably smaller (Flood, 1964; Fremouw, 1966).

An alternative explanation of the data leading to conclusions 2 and 3 above is that irregularity height decreases with increasing latitude and K index. Presently available information fails either to support or definitely reject this possibility.

From the analysis of part of our data by the two-frequency correlation technique and comparison with the scintillation-ratio results, we have concluded that the former suffers from the influence of large-scale refraction effects. The result is an underestimation of the scale of scintillation-producing irregularities.

At VHF and low UHF, a frequency ratio of about three is useful for either technique under normal conditions in the auroral zones. However, the correlation technique is not reliable in the lower portion of this range because of refractive effects.

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